GOME NRT Satellite Observations during the THESEO2000, SOLVE, and TOPSE Campaign

Final Report

D.W. Arlander[1], K. Bramstedt[2], J.P. Burrows[2], M. Chipperfield[3],
K.-U. Eichmann[2], U. Platt[4], A. Richter[2], B.-M. Sinnhuber[3],
T. Wagner[4], M. Weber[2†], M. Wenig[3], and F. Wittrock[2]

[1] Norwegian Institute for Air Research (NILU), Kjeller
[2] University of Bremen, Bremen
[3] University of Leeds, Leeds
[4] University of Heidelberg, Heidelberg

http://www.iup.physik.uni-bremen.de/gomenrt2000

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[†] corresponding author: e-mail to mark.weber@iup.physik.uni-bremen.de

Contents

1 Introduction

The Global Ozone Monitoring Experiment Near Real Time Campaign (GOME NRT) 1999/2000 was set up as a support for the three major measurement campaigns THESEO 2000 (Third European Stratospheric Ozone Experiment), SOLVE (SAGE III Ozone Loss and Validation Experiment), and TOPSE (Tropospheric Ozone Production about the Spring Equinox) during the period between December 1999 and May 2000. This was a joint collaboration between the Institutes of Environmental Physics (IUP) at the Universities of Bremen and Heidelberg, respectively, the German Remote Sensing Data Centre part of the German Aerospace Centre (DLR/DFD), the Space Research Organisation (SRON, The Netherlands), the Norwegian Institute for Air Research (NILU, Norway), the Swedish Space Corporation (SSC, Sweden), the European Ozone Research Coordinating Unit (EORCU, UK), the European Space Agency ESA, and the National Center for Atmospheric Research (NCAR, Boulder) and was supported in parts by the EU funding within the GODIVA and EUROSOLVE projects.

The NRT data products derived from the GOME spectral data encompass ozone total columns and profiles, total columns of NO_2 and BrO, and slant columns of OClO. The NRT raw data products (radiance and solar irradiance) were processed by the GOME data processor (GDP) located at ESA's Kiruna ground station, which is one of five ESA stations receiving global data from the ERS-2 (European Remote Sensing satellite) carrying GOME. The GDP was developed and operated by DLR/DFD in Oberpfaffenhofen. Except for total ozone which was provided by the GDP Kiruna, all NRT level-2 products were generated by the Universities of Bremen and Heidelberg and NILU from the processed NRT level-1 data and displayed at the IUP University of Bremen web site (www.iup.physik.uni-bremen.de/gomenrt2000). The internet connection between ESA Kiruna ground station and NILU for the level-1 data transmission was kindly provided by the Swedish Space Corporation. The GOME NRT level-1 data were collected and stored at the NILU database.

THESEO was an European measurement campaign to study the anthropogenic effects on the ozone depletion and the links between tropics, mid latitudes, and the North polar region and between the lower stratosphere and the upper troposphere. It was funded by the European Commission DG XII-D1 and coordinated by the European Ozone Research Coordinating Unit (EORCU).

The SAGE III Ozone Loss and Validation Experiment (SOLVE) is an American measurement campaign designed to examine the processes controlling ozone levels at mid- to high latitudes. Measurements were made in the Arctic high-latitude region in winter using the NASA DC-8 and ER-2 aircrafts as well as balloon platforms and ground-based instruments.

This winter THESEO2000 and SOLVE were joined to undertake the largest field campaign ever over the Arctic involving more than 350 scientists. This brief report summarises the contribution of GOME satellite observations to both campaigns (Section 2). A summary of all activities within THESEO2000 is given in the EORCU Report (Appendix). GOME NRT data were also used for detecting tropospheric trace gases such as BrO in support of TOPSE (Section 3).

2 Stratospheric GOME Observations

2.1 Chlorine Activation and Denoxification

First signs of chlorine activation were observed by GOME in the middle of December. As stratospheric temperature continued to decrease to record levels in January, extended areas inside the polar vortex contained low nitrogen dioxide vertical columns and high OClO slant columns, the latter a sign that large chlorine activation has taken place.

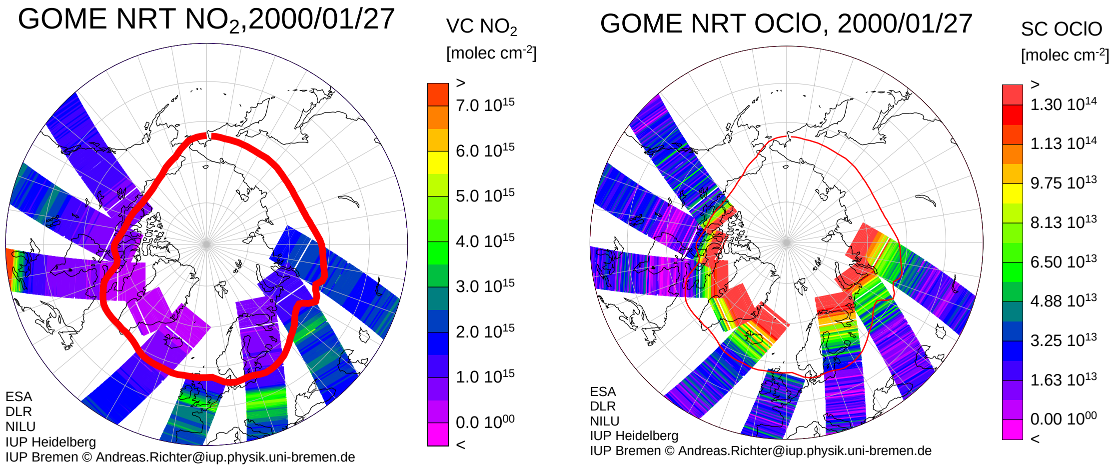

Figure 1: NO_2 vertical (left) and OClO slant column (right) distribution on 27 January 2000. The 38 PVU contour at $\theta = 475$ K ($\sim$19 km altitude) indicating the polar vortex edge is shown in red.

Figure 1 shows the nitrogen dioxide and OClO column distribution on 27 January 2000. OClO is only observed at twilight since it rapidly photolyses at increasing solar zenith angles. For the same reason no attempts have been made to convert OClO slant columns into vertical ones.

High OClO and low NO_2 levels inside the polar vortex agree with the presence of polar stratospheric clouds (PSCs), which were frequently sighted in December and January. During January UKMO temperatures at 46hPa were close and below that of possible (ice) PSC II formation. The low NO_2 total column amounts detected by GOME in late winter may be a sign for large scale denitrification by sedimentation of non-gas phase HNO_3 inside the polar vortex. High OClO levels still persisted throughout February and low NO_2 vertical columns below $\sim 0.7 \times 10^{15}$ molec/cm^2 were still detected by GOME in late February.

2.2 Total Ozone

Table 1 summarises the monthly mean ozone within the polar vortex derived from GOME in February and March since 1996. This winter the February and March mean values of 350 DU and 341 DU, respectively, are comparable to the cold winters 1995/1996 and 1996/97. The March mean north of 63°N were at a record low in 1996 and 1997 if one also includes the longterm TOMS record starting in 1979. This year the corresponding GOME mean north of 63°N is 365 DU, clearly lower than in the two previous seasons and approximately equal to the record values from 1996 and 1997 (see Table 2).

The average March ozone distribution of the five most recent spring seasons are collected in Fig. 2. Low total ozone is clearly visible inside the mean polar vortex in 1996, 1997, and

Table 1: NH monthly mean total ozone in regions where PV at 475 K (~19 km altitude) is greater than 38 PVU.

Year	GOME Tot. O_3 [DU]		
	February	March	April
1996	357	357	– [a]
1997	386	351	353
1998	370	403	– [a]
1999	419	490	– [a]
2000	351[b]	345[b]	n/a

a sample too small or zero

b Values based upon NRT data

Table 2: NH March monthly mean total ozone 63°N – 90°N

March GOME Tot. O_3 63-90°N					
Year	1996	1997	1998	1999	2000
O_3 [DU]	370	360	426	447	365[a]

[a] preliminary values based upon NRT data

2000, while the overall Arctic ozone levels were comparatively high in 1998 and 1999. Two cold winter/spring seasons were followed by two warm winters (1997/98 and 1998/99). This winter/spring season again matches the series of cold winters during the nineties. These images also document the large inter annual variability in total ozone in late winter and early spring. Interesting to note is the shifting of the mean polar vortex location each year. This winter the vortex position was on average located above the Siberian Sea in March (Fig. 2).

2.3 GOME-SLIMCAT Model Comparison of Total Ozone

In Fig. 3 the GOME total ozone distribution from 11–12 March 2000 is compared with results from the 3D chemical transport model (CTM) SLIMCAT. The model was forced with meteorological analysis from the UKMO UARS data set starting in October 1991. Passive ozone tracer was initialised in December 1999. There is good agreement between GOME and the model calculation; the model values are slightly enhanced compared to the satellite observations. From the comparison with the modelled passive ozone tracer, it can be concluded that about 60–120 DU in the total column has been depleted. Average chemical loss north of 63° is about 75 DU. At the end of March chemical ozone loss

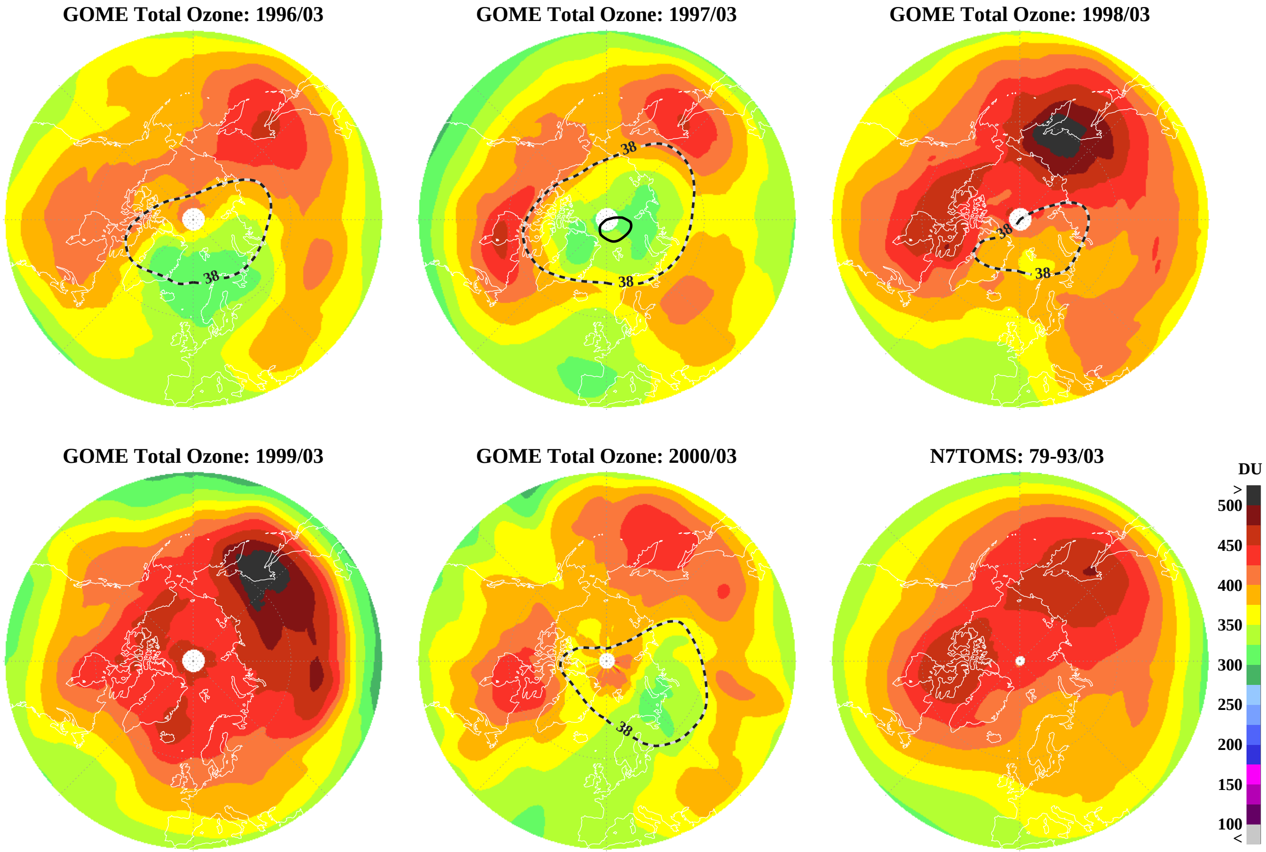

Figure 2: Arctic March mean total ozone from GOME during the years 1996-2000 (from left to right and top to bottom). The 1979-1993 average derived from TOMS/Nimbus7 is shown in the bottom row to the right. Mean polar vortex position (dashed line: 38 PVU at θ =475 K (~19 km altitude)) and cold stratospheric temperature region (solid line: T=195 K at 475 K) are also shown.

amounted to about 100–140 DU, which was about 30% of the total column. The low total ozone observed inside the polar vortex was also partially due to low stratospheric temperatures and to transport.

Figure 4 shows the GOME vertical ozone distribution in a latitude-altitude chart representing one GOME orbit on 13 March 2000. The selected orbit was close to 40-45°E longitude. North of about 57°N a band of minimum ozone is observed near 15 km altitude coinciding with the temperature minimum (~ 205 K) located below the polar vortex.

2.4 Chemical Ozone Loss at 475 K

Using the GOME vertical ozone profiles, average volume mixing ratios within the polar vortex have been determined for selected days between 18 February and 18 March 2000 (Fig. 5). The vortex values are restricted to the region, where the solar zenith angle (SZA)

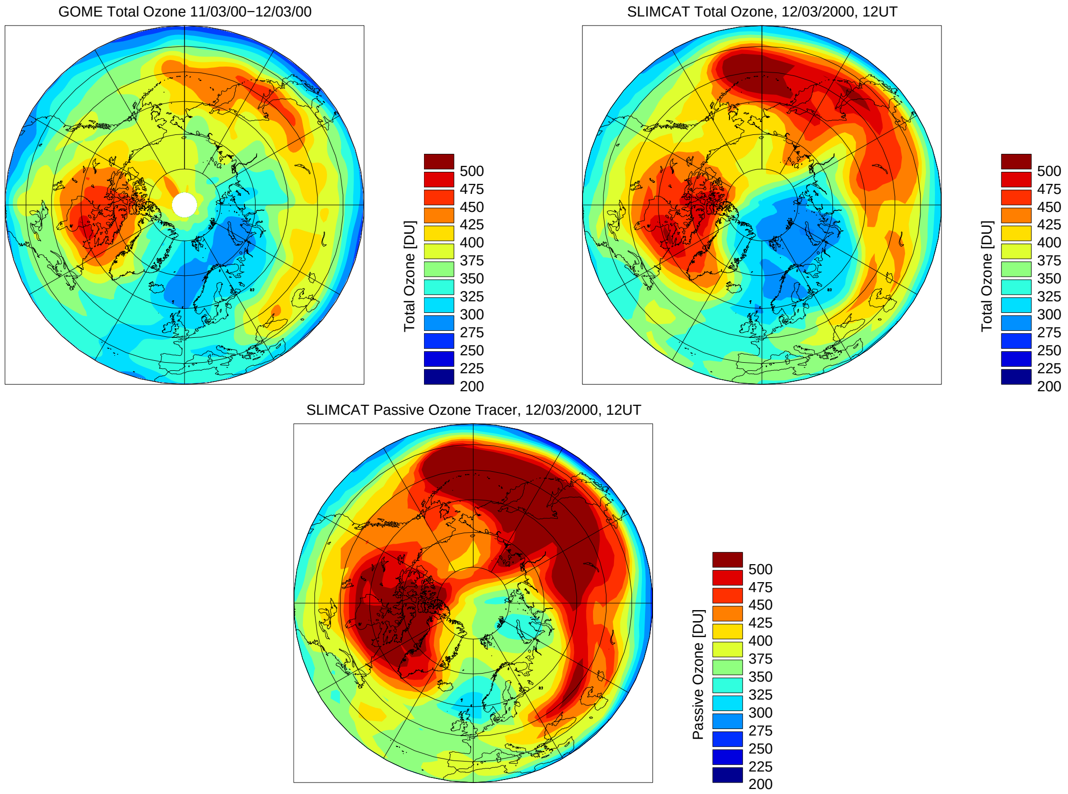

Figure 3: Ozone distribution on March 12, 2000. Left: GOME total ozone (11-12 March). Right: SLIMCAT total ozone. Bottom: SLIMCAT passive ozone tracer.

was below 75°. At higher SZA the integration times of the spectral measurements are increased resulting in a large ground pixel size where the geolocation parameters (among them SZA) strongly vary across the pixel area, thus complicating the profile retrieval. This means that vortex coverage by the GOME profiles increases with time during late winter and early spring.

Average diabatic ozone changes at the isentropic level were calculated using a broadband radiation transfer scheme. After subtracting the diabatic ozone changes from the mean daily volume mixing ratios an average chemical loss rate of 27 ppbv/day was estimated during the period between 12 February and 15 April 2000 resulting in a mean chemical loss of about 50% at the 475 K isentropic level (Fig. 5). 475 K potential temperature corresponds to an approximate altitude of 19 km. The starting values of the ozone mixing ratios in middle of February are based upon a rather limited number of ozone profiles and its larger uncertainty may, therefore, affect the mean derived loss rates.

At 550 K isentropic level (∼22 km altitude) an average chemical loss rate of 20 ppbv/day was derived, which lead to an accumulated ozone loss of about 32% between middle of February and middle of April (Fig. 5).

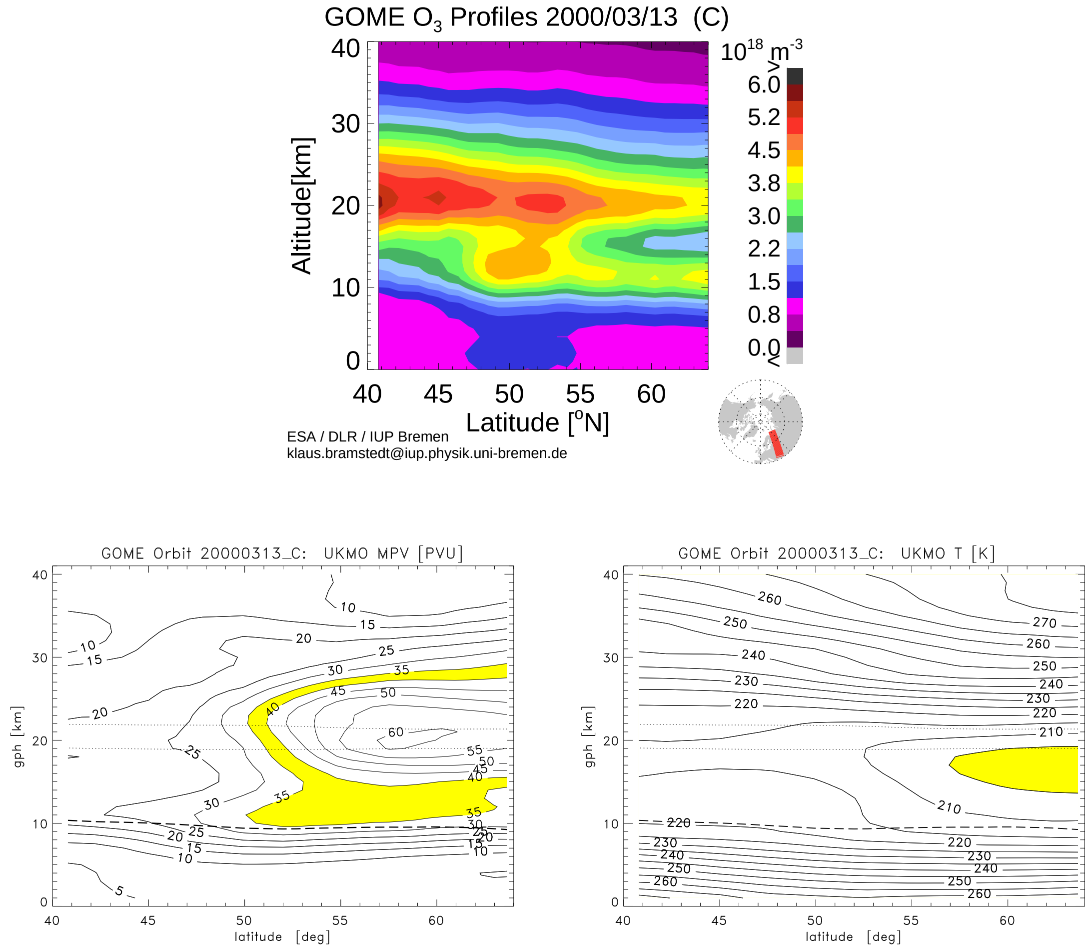

Figure 4: Top: latitude-altitude chart of GOME ozone on 13 March 2000; bottom left: corresponding MPV chart of the GOME orbit. Polar vortex regions is bounded by the shaded region. MPV is the modified potential vorticity referenced to θ =475 K (~19 km altitude); bottom right: temperature latitude-altitude chart. Meteorological analysis are derived from the UKMO UARS dataset.

3 Tropospheric BrO observations in Spring 2000

Observations in the Arctic and Antarctic have shown, that with polar sunrise ozone depletion occurs not only in the stratosphere, but also in the boundary layer (BL). Catalytic cycles involving bromine and recycling mechanisms on aerosols are thought to be responsible for these events that can deplete BL ozone below detectable concentrations for days or even weeks. In contrast to the stratosphere, the origin of the bromine in the polar boundary layer is not anthropogenic, but natural sea salt, probably released from sea spray in a complicated activation mechanism on fresh sea ice.

Polar boundary layer low ozone events are characterised by rapid changes in a number of atmospheric trace gases and aerosols, including mercury compounds. Recent studies

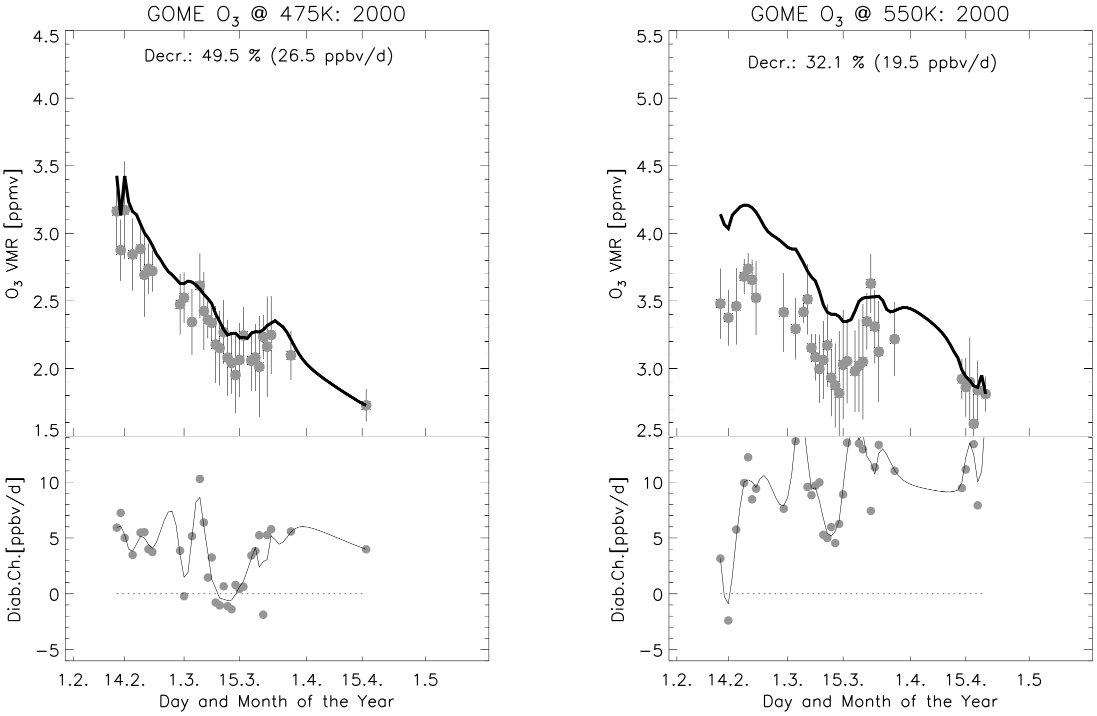

Figure 5: Mean polar vortex GOME ozone volume mixing ratio (>38 modified PVU) at the isentropic levels of 475 K (left, ~19 km altitude) and 550 K (right, ~22 km altitude). Error bars indicate the one standard deviation from averaging. Solid curve yields the ozone mixing ratios after adding modelled diabatic ozone changes as shown in the bottom backward from the last date. A mean chemical ozone loss of about 50% (26 ppb/day on average) and 32% (20 ppb/day on average) at 475 K (left) and 550 K (right) during the period 12 February - 15 April 2000 has been deduced (dashed line).

have shown, that during these events large amounts of volatile mercury compounds from anthropogenic emissions are converted into particulate forms and deposited onto snow and ice. When temperatures increase in late spring, mercury is introduced into the polar marine ecosystem and accumulates in plankton, fish and also humans depending on sea food.

With the GOME instrument, it is for the first time possible to monitor BrO in the atmosphere from space. While the detection of stratospheric BrO has been anticipated for the GOME instrument, it has become clear in the last years that BrO events associated with low ozone in the polar boundary layer can be easily detected from GOME data. As an example, GOME BrO columns for March 2000 are shown in figure 6. Typical columns for stratosphere and free troposphere are of the order of 5×10^{13} molec/cm^{-2} at this time of the year. Much larger values are detected along the coast lines, in the Hudson Bay area and over sea ice and are attributed to boundary layer BrO.

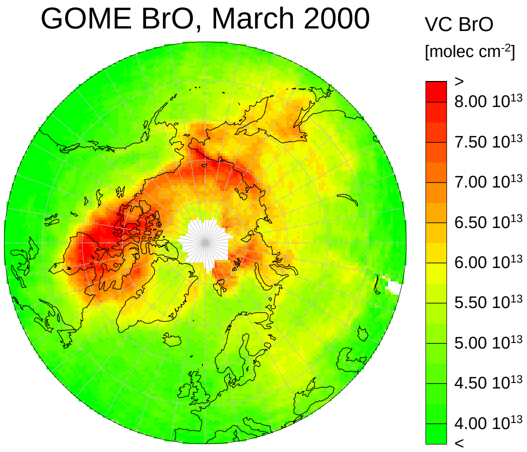

Figure 6: GOME BrO columns in March 2000. Both stratospheric and tropospheric BrO contributes to the total columns, 5×10^{13} molec/cm^{-2} being a typical value for stratospheric columns at this time of the year. Regions with enhanced BrO in the boundary layer are detected along the coast lines, in the Hudson Bay area and over sea ice. Similar patterns have been observed in previous years.

GOME near real time BrO plots have been used in the TOPSE experiment for mission planing and also for the interpretation of ground-based and air borne measurements to identify regions with tropospheric low ozone events. During and after the NRT campaign, updated data sets have been requested by a number of research groups, including NCAR, the Oak Ridge National Laboratory, Lamar University, the University of Jena and others, demonstrating the usefulness of the GOME BrO maps.

4 Summary of Scientific Highlights

The following conclusion can be drawn from the GOME observations:

- In terms of total ozone and stratospheric temperatures, this Arctic winter 1999-2000 resembles the extreme cold winter/spring season in 1995-96 resulting in record low mean total ozone inside the polar vortex during February and March.
- In January and February high OClO slant column amounts were derived from GOME observations indicating large scale chlorine activation inside the polar vortex. This is a prerequisite for catalytic depletion of ozone. Low NO_2 vertical columns measured by GOME with values below $\sim 0.7 \times 10^{15}$ molec/cm^2 may indicate large scale denitrification due to sedimentation of large ice particles containing HNO_3. Removal of HNO_3 from certain altitude levels slows down the ozone recovery in spring since NO_x (partially released through photolysis of HNO_3) is needed for conversion of reactive chlorine compounds into their reservoir species.

- Comparison between GOME total ozone and 3D CTM model calculation show that on average about 100–140 DU of the total column were chemically depleted between December and end of March (30% of the total column). Part of the very low ozone observed in winter 1999/2000 are of dynamic origin related to very low temperatures encountered in the lower stratosphere.
- From the ozone profile analysis 50% chemical ozone loss at 475 K (∼19 km altitude) between middle of February and middle of April were deduced. After middle of March the ozone volume mixing ratio inside the polar vortex decreased to below 2 ppm, which is about 0.5 ppm lower than in mid March 1997. At 550 K (∼22 km altitude) an accumulated chemical ozone loss of 32% (average of 20 ppbv/day) was observed by GOME.
- Tropospheric BrO events were observed throughout the Arctic, in particular along the coast lines and over sea ice, in late winter and spring. These observation confirmed that the BrO plumes are a regular feature in the Arctic planetary boundary layer in spring.

A detailed report of the most recent Arctic measurement campaign, which also included the major findings reported here, is provided by the THESEO2000 winter report (see Appendix) which was compiled by the EORCU.

5 External Usage of GOME NRT Level-1 data

Kelly Chance from Smithsonian Astrophysical Society (SAO) accessed the GOME NRT level-1 database for additional scientific studies. His activities are summarised in the following e-mail:

Date: Thu, 3 Aug 2000 18:28:42 +0000 (GMT)
From: Kelly Chance <kchance@cfa.harvard.edu>
To: Mark Weber <weber@gome5.physik.uni-bremen.de>
Subject: GOME NRT data

Dear Mark,

I am providing gas measurements from GOME (particularly BrO and OClO) for the U.S. SOLVE project. The use of GOME NRT was very convenient for this purpose, because it let us quickly see that there were no problems with our fitting of the data. However, as it is the final data that are critical for analysis in the context of SOLVE, and we did not provide feedback that influenced mission planning, the availability of NRT data was not critical to us in this particular case.

Next Spring I will be participating in the U.S. TRACE-P mission, where the availability of NRT data from GOME could be much more important to the mission planning. TRACE-P is a tropospheric experiment, and we would be supplying GOME results for tropospheric

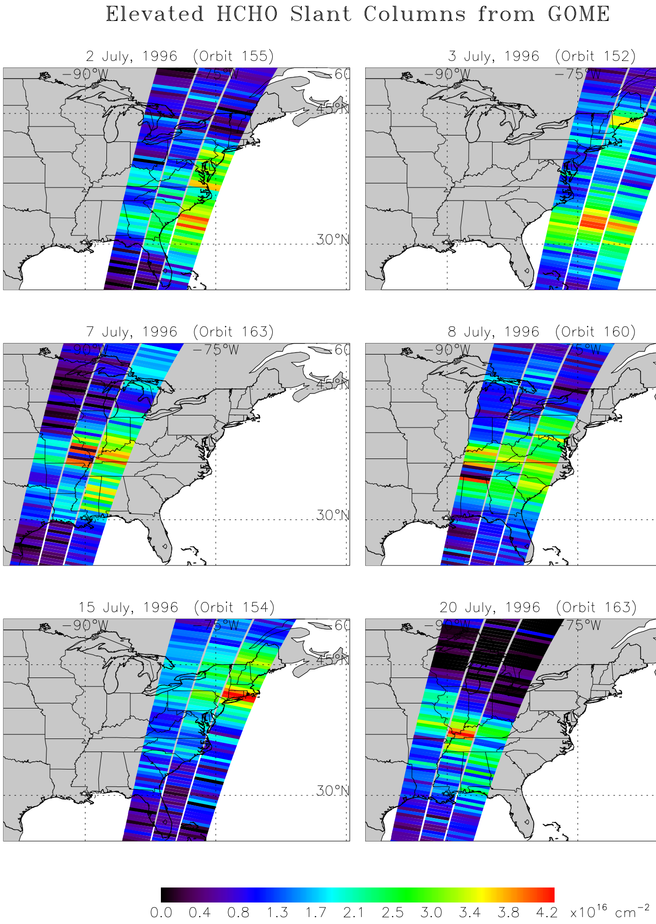

Figure 7: Evolution of tropospheric formaldehyde from GOME in early July 1996 above Eastern USA (courtesy of K. Chance).

gases (e.g., O3, NO2, HCHO) and aerosols quickly enough so that they could be used in the planning of the aircraft flights. The scientific planners for TRACE-P have already requested that GOME NRT data be available, and I believe we will be discussing this at the next GSAG (Gome Science Advisory Committee)*. As an illustration of just how useful such data might be, I have attached a figure showing some details of production and transport of formaldehyde* (Figure 7)*; the NRT availability of this sort of data for the GOME tropospheric species is obviously useful in deciding when and where to fly the planes.*

I would like to add that I found the ESA colleagues extremely helpful in making sure that I had full access to the NRT data.

Best regards,
Kelly

Table 3: Access Statistics of University of Bremen NRT Web Pages.

	KBytes	Visits	Pages	Files	Hits
Totals	472771	3037	12947	46230	63458
per day	2781	17	76	271	371
per day March 2000	-	39	177	527	663

Table 4: Usage of University of Bremen NRT- Web Pages: Top ten countries of a total of 32 countries in March 2000.

#	Files		Country
1	5391	34.09%	Germany
2	2745	17.36%	US Commercial
3	2062	13.04%	Unresolved/Unknown
4	1066	6.74%	Network
5	761	4.81%	US Educational
6	428	2.71%	Norway
7	523	3.31%	Netherlands
8	225	1.42%	Austria
9	371	2.35%	United Kingdom
10	340	2.15%	Italy

6 Statistics on the Access to the NRT Webpages

During the THESEO2000 campaign the access to the NRT–Web pages at the University of Bremen were continously logged. The access statistics between 14 December 1999 and 31 May 2000 is summarised in Table 3. *Hits* counts all requests to the server, *Files* counts all files delivered, *Pages* are the number of accessed HTML pages and *Visits* summarises all accesses from the same client computer within 30 minutes, which are counted as one visit to the web site. For the whole time period the server was visited about 17 times per day. In February and March 2000 a maximum of about 40 visits per day were observed.

Accesses came from computers all over the world. In March 2000 users from 474 different computers in about 30 countries had a look at the NRT service of the University of Bremen. The top 10 countries are listed in Table 4. Most requests were from Germany and the United States (US Commercial and US Educational). Unresolved are computers without official names. About half of the traffic from Germany was caused by the University of Bremen, which included regular maintenance services. This statistics confirmed the tremendous world wide and public interest in the GOME NRT data.

7 Outlook

Near-real–time GOME data were very useful for the mission planning during THESEO2000 and SOLVE Arctic winter campaign. In addition scientific results from the analysis of the GOME NRT data complemented and confirmed field measurements which took part in the joint US–European Arctic campaign THESEO2000/SOLVE. Without having the GOME data in NRT the contribution to THESEO2000 as documented in the EORCU Report would not have been possible. The latter report was published in April 2000 before regular operational GOME data were available.

Last winter GOME documented large scale chemical ozone depletion in a cold stratospheric winter, which matched the series of cold winters in the mid nineties. There is a large interest in the scientific community that in the coming winter GOME NRT data may become available to aid in the assessment of future Arctic ozone depletion (see EORCU planning document for next winter in Appendix). Stratospheric chlorine loading in the stratosphere has been stagnating recently as a consequence of the Montreal Protocol and its amendments indicating that a turnaround point has been reached. However, recent climate studies indicate that increasing greenhouse gases, particularly CO_2, may be responsible for a cooling trend in the stratosphere. This would mean that cold stratospheric winters may become more frequent in the Arctic delaying the recovery of ozone by a decade or more.

Furthermore GOME NRT data are very useful in tracking tropospheric trace gases such as BrO, which show strong regional enhancements during spring. Formaldehyde is an additional tropospheric trace constituent which may be included in future NRT data analysis.

From the scientific and public view point there is considerable interest to continue GOME NRT activities in the near future to support mission plans in upcoming field campaigns and to provide a quick scientific and public assessment of the future state and development of the chemical composition of the atmosphere.

8 Acknowledgement

The support of the European Space Agency (ESA) and the German Aerospace Centre (DLR/DFD) to deliver the GOME NRT data products is gratefully acknowledged. Parts of this activity were funded by the EU within the GODIVA and EUROSOLVE projects. Without the permission by the Swedish Space Corporation internet linking with ESA Kiruna ground station would not have been possible. We thank the United Kingdom Meteorological Office (UKMO) for providing the meteorological data set and we thank K. Shine for making the broadband radiative transfer scheme for diabatic heating rate calculation available to us.

9 Appendix

- Letter of Acknowledgement from EORCU
- EORCU Planning Document for the Arctic winter 2000/01
- EORCU Arctic winter 1999/2000 Report: The northern hemisphere stratosphere in the winter and spring of 1999/2000